(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 741 316 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
06.11.1996 Bulletin 1996/45

(51) Int. Cl.[6]: G02F 1/015, G02F 1/025, H04B 10/18, H01S 3/025

(21) Application number: 96201982.4

(22) Date of filing: 03.02.1993

(84) Designated Contracting States:
DE FR GB IT

(30) Priority: 03.02.1992 JP 46390/92
23.04.1992 JP 129353/92

(62) Application number of the earlier application in accordance with Art. 76 EPC: 93300773.4

(71) Applicant: KOKUSAI DENSHIN DENWA KABUSHIKI KAISHA
Shinjuku-ku Tokyo-to (JP)

(72) Inventors:
- Suzuki, Masatoshi
  Kasashima-Machi, Saitama-ken (JP)
- Tanaka, Hideaki
  Koganei-Shi, Tokyo-To (JP)
- Matsushima, Yuichi
  Tokorozawa-Shi (JP)

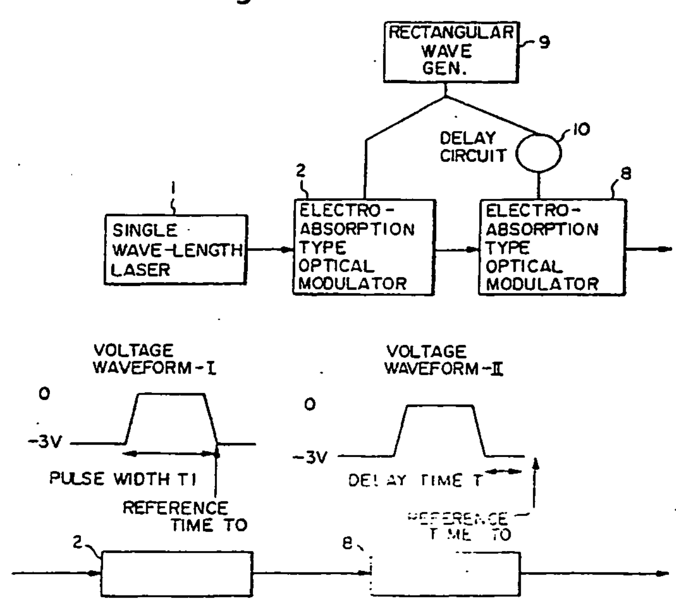
(74) Representative: Crawford, Fiona Merle et al
Elkington and Fife
Prospect House
8 Pembroke Road
Sevenoaks, Kent TN13 1XR (GB)

Remarks:
This application was filed on 13 - 07 - 1996 as a divisional application to the application mentioned under INID code 62.

(54) **Optical pulse generator**

(57) An optical pulse generator for optical soliton communications comprising a semiconductor laser (1) and two semiconductor electro-absorption type optical modulators (2,8), the first of which modulates the output light from the laser (1), and the other of which modulates the output of the first, whereby a time delay is introduced between the voltages impressed on the optical modulators.

Fig. 2A



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provision of: a semiconductor laser which oscillates continuously at a single wavelength; a first optical modulator which performs intensity modulation of the output light of the semiconductor laser; a second optical modulator which performs intensity modulation of the output light of the first optical modulator; a rectangular wave generator which generates a rectangular pulse voltage for driving the first and second optical modulators; and a delay circuit which is provided between the second optical modulator and the rectangular wave generator to delay the rectangular pulse voltage of the rectangular voltage generator for a predetermined period of time.

In still another aspect, the present invention relates to an optical pulse generator which is characterized by the provision of: a semiconductor laser which oscillates continuously at a single wavelength; a first semiconductor electro-absorption type optical modulator which performs intensity modulation of the output light from the semiconductor laser; a second semiconductor electro-absorption type optical modulator which performs intensity modulation of the output light from the first semiconductor electro-absorption type optical modulator; a sinusoidal voltage generator which generates a sinusoidal voltage for driving the first and second semiconductor electro-absorption type optical modulators; a DC voltage generator which applies a reverse DC voltage to the first and second semiconductor electro-absorption type optical modulators; and a delay circuit which is provided between the second semiconductor electro-absorption type optical modulator and the sinusoidal voltage generator to delay the sinusoidal voltage of the sinusoidal voltage generator for a predetermined period of time.

The first-mentioned optical pulse generator applies semiconductor laser beams of a fixed intensity to the semiconductor electro-absorption type optical modulator and generates therefrom optical pulses through utilization of a nonlinear characteristic of the optical modulation so that its optical output shows a monotonous decrease substantially exponentially with an increase in the applied voltage. This characteristic is inherent in the semiconductor electro-absorption type optical modulator and is not found in a dielectric optical modulator whose optical output periodically varies with an increase in the applied voltage. By applying to the semiconductor electro-absorption type optical modulator a DC voltage biased to a point where its optical output is sufficiently attenuated and then by applying to the optical modulator a sinusoidal voltage of an amplitude about twice that of the DC voltage, the optical output pulse of the optical modulator automatically becomes shorter than the sinusoidal voltage by virtue of its nonlinear optical output characteristic mentioned above and the semiconductor electro-absorption type optical modulator can be operated so that it becomes transparent for a short period of time. Thus, short optical pulses can be generated. The temporal waveform of the optical pulse obtainable with this method is intermediate between squared hyperbolic secant and Gaussian waveforms. By changing the bias voltage from a value at which to obtain an extinction ratio of 10 dB to a value at which to obtain an extinction ratio of 50 dB and by setting the amplitude of each modulating voltage to twice that of the bias voltage, the full width at half maximum of the optical pulse obtainable in this instance changes from 25 to 10% of the period of the sinusoidal voltage. Moreover, since the semiconductor laser is caused to oscillate at a fixed wavelength and since the short optical pulses are produced by the semiconductor electro-absorption type optical modulator without directly modulating the semiconductor laser, the oscillation wavelength of the semiconductor laser is free from variations which are caused by the direct modulation of the laser, and hence it is possible to suppress excessive broadening of the spectrum, thus providing optical soliton pulses.

With the second-mentioned optical pulse generator, semiconductor laser beams of a fixed intensity are applied to the first optical modulator driven by a rectangular voltage which provides a sufficient extinction ratio, and the output light of the optical modulator is applied to the second optical modulator driven by a rectangular voltage which has a time difference between it and the above-mentioned rectangular voltage. By this, the AND operation of the driving waveform is performed in an optical domain, thereby generating short optical pulses. The generation of a very short voltage pulse waveform needs an ultrahigh-speed electronic circuit, and hence is difficult. In contrast thereto, the present invention permits the production of short optical pulses by use of relatively long rectangular voltage pulses. Since the optical pulse width can be changed arbitrarily by setting the time difference between the two rectangular voltage pulses, it is possible to produce an optical pulse shorter than that obtainable with the first-mentioned optical pulse generator. The optical modulators may be either semiconductor electro-absorption type optical modulators or dielectric optical modulators.

With the third-mentioned optical pulse generator, semiconductor laser beams of a fixed intensity are applied to the first semiconductor electro-absorption type optical modulator driven by a bias voltage and a sinusoidal voltage of an amplitude more than twice that of the bias voltage and the output light of the first optical modulator is applied to the second semiconductor electro-absorption type optical modulator driven by a bias voltage and a sinusoidal voltage which has a time difference between it and the above-mentioned sinusoidal voltage and has an amplitude more than twice that of the bias voltage. By this, short optical pulses are produced. By driving the semiconductor electro-absorption type optical modulator with a sinusoidal voltage of an amplitude more than twice that of the bias voltage, an optical pulse waveform of very short rise and fall times can be obtained owing to the nonlinearity of the optical output characteristic. By clipping the optical output pulse of the first semiconductor electro-absorption type optical modulator by the second semiconductor electro-

(an extinction ratio of 20 dB) that in the case of the bias voltage being zero. Furthermore, by applying a 5-GHz sinusoidal modulation voltage of a 6 V amplitude to the optical modulator, an ultrashort optical pulse was obtained which had a full width at half maximum of 40 picoseconds. When the bias voltage was changed from -2 V to -6 V and the amplitude of the bias voltage was set twice the bias voltage, the full width at half maximum of the optical pulse changed from 49 picoseconds to 22 picoseconds. Since the period of the sinusoidal voltage was 200 picoseconds, pulse widths in the range of 24.5 to 11% of the period were obtained.

The present invention does not use such an optical resonator as in the case of the prior art example, and hence permits arbitrary setting of the modulation rate. In the tests of this embodiment, the frequency of the sinusoidal voltage was set to 15 and 20 GHz. When the bias voltage was -2 V and the amplitude of the sinusoidal voltage was 7.2 V, short optical pulses whose full widths at half maximum were 14 and 11 picoseconds were obtained when the frequency of the sinusoidal voltage was 15 and 20 GHz, respectively. Since the 3 dB bandwidth of the frequency characteristic of the optical modulator used was 7 GHz, the modulation efficiency at 15 and 20 GHz was 4 and 6 dB lower than that in the case of DC voltage. It was found, however, that the modulation rate could freely be selected, in principle, by increasing the modulating voltage in a manner to make up for such deterioration of the modulation efficiency.

Next, measurements of light spectrums were made. The full widths at half maximum of the spectral envelope of temporal waveforms which has repetition frequencies of 5 and 15 GHz and full widths at half maximum of 22 and 14 picoseconds were 14 and 23 GHz, respectively. The product of the full width at half maximum of the temporal waveform and the full width at half maximum of the spectral envelop was 0.32 in either case. This value is very close to the product, 0.315, of the full width at half maximum of the temporal waveform and the full width at half maximum of the spectral envelope of the squared hyperbolic secant waveform which is the requirement for the soliton pulse. The optical pulse obtainable with the present invention substantially satisfies the soliton requirement and has a pulse width to be 20% of or smaller than the pulse interval, and hence it can be applied to the soliton fiber optic communication system. Then, a train of short pulses having a 60 psec full width at half maximum and a 2.48 GHz repetition frequency, produced by the pulse generator of this embodiment, was transmitted over an optical fiber 10,000 km long and pulse waveforms were observed. No remarkable deterioration was observed in the pulse waveforms even after the pulses were transmitted 10,000 km. This proves that the optical pulse generator of this embodiment can be used as a soliton light source for a long distance optical soliton communication.

Incidentally, the light output characteristic in logarithmic scale or the extinction ratio scaled in dB of the electro-absorption type optical modulator need not always be linear to the applied voltage. In the case where the extinction ratio linearly increases in a low voltage region and the rate of its increase in a high voltage region slightly lowers, the resulting temporal waveform becomes closer to the squared hyperbolic secant waveform. This phenomenon was observed when the optical axes of an optical fiber and optical modulators disposed at its input and output ends with lenses or the like interposed therebetween were slightly out of alignment.

In the case where the extinction ratio scaled in dB linearly increases in the low voltage region and the rate of its increase slightly increases in the high voltage region, the resulting temporal waveform becomes very close to the Gaussian waveform. In either case, such a waveform variation is permissible in the case of the soliton light source. Moreover, when the wavelength of light incident to the optical modulator was changed from 1.52 to 1.57 μm in this embodiment, short optical pulses of about the same waveform could be obtained.

The pulse generator of this embodiment permits easy adjustment of the pulse width, and hence can be used not only to generate optical soliton pulses but also as an optical pulse generator which utilizes ordinary return-to-zero codes. The optical pulse generator of this embodiment does not employ an optical resonator, and hence is advantageous in that it is insusceptible to changes in temperature and other environmental conditions, that the modulation rate is variable, and that short optical pulses for the soliton communication, which is free from excessive spectral line broadening, can easily be generated by use of only the sinusoidal voltage without the necessity of using a special microwave voltage generator.

It is postulated that a practical application of this embodiment will involve the use of a second optical modulator, as shown in Fig. 10, for generating an information signal which is added to the output light of the semiconductor electro-absorption type optical modulator 2.

[Embodiment 2]

Fig. 2A is a block diagram illustrating a second embodiment of the present invention and Fig. 2B is a diagram for explaining the principle of generating a short pulse. A feature of this embodiment resides in the generation of short pulses by driving two electro-absorption type optical modulators with modulating voltages of different durations unlike in Embodiment 1.

Fixed output light of a 1.55 μm wavelength, emitted from an InGaAsP λ/4 shift DFB single-wavelength laser 1, is applied to a first InGaAsP electro-absorption type optical modulator 2. The first optical modulator 2 is driven by a rectangular voltage (pulse width T1) of a 3 V amplitude (0 to -3V) and a 5 GHz repetition frequency, which is one of two outputs branched from the output of a rectangular wave generator 9. Since the rectangular voltage generator 9 can generate a pulse voltage whose

2 used in the optical pulse generator of Embodiment 1 are integrated on an InP semiconductor substrate 11. Both elements are electrically isolated by a semi-insulating InP layer 12.

The inventors made an integrated device in which the laser portion was 300 μm long, the semi-insulating InP layer 12 was 50 μm long and the modulator portion was 290 μm long. Either end face of the integrated device is coated with an anti-reflection film to suppress variations in the oscillation wavelength which is caused by the reflection of light from the optical modulator to the laser. The electric isolation resistance between the laser and the optical modulator is 1 megohm and suppresses the electric interference between them. The isolation resistance of 1 megohm is enough large to suppress wavelength variations of the laser and to obtain the transform-limited short pulses. The forbidden band energy of an InGaAsP modulating waveguide layer is 1.45μm. When a 180 mA direct current was applied to the laser portion, it oscillated at a single wavelength of 1.55 μm, and when a -2 V bias voltage was applied to the modulator portion, an extinction ratio of 25 dB was obtained. Moreover, when a sinusoidal voltage of a 5 GHz frequency and a 4 V amplitude was provided to the optical modulator portion, an optical pulse was obtained the full width at half maximum of which was 33 picoseconds. It was ascertained that the product of full width at half maximum of the temporal waveform and the full width of half maximum of the spectral envelope was 0.31, which is very close to the value of 0.315 for transform-limited $sech^2$ pulse and sufficient for the soliton light source.

While this embodiment has been described to employ an InGaAsP λ/4 shift DFB laser as the single-wavelength laser, it may also be replaced by other single-wavelength lasers of any construction, such as a distributed Bragg-reflector laser and an ordinary DFB laser using a homogeneous or uniform diffraction grating, and a variable wavelength laser is also applicable. Moreover, this embodiment is not limited specifically to semiconductor materials of any particular series, and a quantum well structure may also be applied to the active layer of the laser and the modulating waveguide layer.

A feature of the optical pulse generator according to this embodiment lies in that since the laser and the modulator are formed as a unitary structure, the optical coupling loss between them is substantially reduced in the one-chip semiconductor device and the DC voltage and the sinusoidal voltage are small because of high modulation efficiency.

[Embodiment 5]

Fig. 5 is a sectional view illustrating (as a part of a fifth embodiment of the invention) a device in which two electro-absorption type optical modulators for generating short pulses are integrated. In this embodiment, the two InGaAsP electro-absorption type optical modulators 2 and 8 used in Embodiments 2 and 3 are integrated on the InP semiconductor substrate 11. Both elements are electrically isolated from each other. The integrated elements are formed by InGaAsP modulating layers of the same composition, and hence provide ease of crystal growth cause no optical coupling loss between them. The electro-isolation resistance between both elements can be made more than 1 megohm by the adoption of the semi-insulating InP layer 12.

An integrated optical modulator for optical pulse generator of this embodiment comprises a semiconductor substrate, a first optical modulator for modulating an intensity of an input light, and a second optical modulator for modulating the intensity of the output light from the first optical modulator, and moreover, the first optical modulator and the second optical modulator are integrated as a unitary structure on the semiconductor substrate.

A feature of this embodiment resides in that no optical coupling loss is caused between the two optical modulators because they are formed as a unitary structure.

[Embodiment 6]

Fig. 6 is a sectional view illustrating (as a part of a sixth embodiment of the present invention) a device in which an electro-absorption type optical modulator for generating short pulses and an electro-absorption type optical modulator for generating information signals are integrated. In this embodiment, the InGaAsP electro-absorption type optical modulator 2 for generating short pulses, used in Embodiment 1, and an InGaAsP electro-absorption type optical modulator 14 for producing information signals are integrated on the InP semiconductor substrate 11, and both elements are electrically isolated from each other by the semi-insulating InP layer 12.

An integrated optical modulator for optical pulse generator of this embodiment comprises a semiconductor substrate, a semiconductor electro-absorption type optical modulator for modulating an intensity of an input light, and an optical modulator for modulating the intensity of the output light from the first optical modulator, and moreover, the semiconductor electro-absorption type optical modulator and the optical modulator are integrated as a unitary structure on the semiconductor substrate.

A feature of this embodiment resides in the additional provision of a signal generating modulator to Embodiment 1 without causing an increase in the optical loss.

[Embodiment 7]

Fig. 7 is a sectional view illustrating (as a part of a seventh embodiment of the present invention) a device in which two electro-absorption type optical modulators for generating short pulses and an electro-absorption type optical modulator for generating information sig-

lizing the nonlinearity of an optical fiber or pulse compression effect by a saturable absorber after the generation of optical pulses by the present invention.

Embodiments of the present invention having a construction such as described above produce the following effects.

The optical pulse generator according to the first aspect of the invention achieves the variable modulation rate and suppresses the excessive spectral line broadening, both impossible with the prior art, by a simple method which employs a semiconductor laser, an electro-absorption type optical modulator, a DC voltage source and a sinusoidal voltage generator, and the pulse generator is capable of generating ultrashort optical pulses free from the excessive spectral line broadening, and hence is very promising as an optical pulse generator for the soliton communication which is stable and reliable for a long period of time.

The optical pulse generator according to the second aspect of the invention is able to produce short optical pulses of arbitrary pulse widths by changing the delay time of a rectangular voltage signal to be applied to one of two optical modulators, and hence is capable not only of achieving the variable modulation rate and suppressing the excessive spectral line broadening but also of easily generating short optical pulses of a pulse width smaller than 1/10 the pulse-repetition period. Hence, this pulse generator is also very promising as an optical pulse generator for the soliton communication.

The optical pulse generator according to the third aspect of the invention is capable not only of achieving the variable modulation rate and suppressing the excessive spectral line broadening but also of easily generating short optical pulses of a pulse width smaller than 1/10 the pulse-repetition period, without the need of using any special high-speed electronic circuit, by changing the delay time of a sinusoidal voltage signal to be applied to one of two electro-absorption type optical modulators. Hence, this pulse generator is also very promising as an optical pulse generator for the soliton communication.

The inventors believe the first-mentioned optical pulse generator is most promising from the viewpoints of easiness of handling of the device and its single-frequency operation and that the third-mentioned optical pulse generator is suitable for generating short optical pulses of smaller pulse widths.

Claims

1. An optical pulse generator for optical soliton communications comprising:

   a semiconductor laser (1) for continuously oscillating an output light at a single wavelength;
   a rectangular wave generator (9) for generating a rectangular pulse voltage;
   a first semiconductor electro-absorption type optical modulator (2) for modulating the intensity of the output light from said semiconductor laser (1) by the rectangular pulse voltage;
   a second semiconductor electro-absorption type optical modulator (8) for modulating the intensity of the output light from said first optical modulator (2) by the rectangular pulse voltage to provide optical short pulses, and
   a delay circuit (10) between said second optical modulator (8) and said rectangular wave generator (9), for delaying the rectangular pulse voltage from said rectangular wave generator for a predetermined period of time.

2. An optical pulse generator according to claim 1, further comprising:

   a third optical modulator (14) for modulating the optical short pulses from said second optical modulator (8) by an information signal.

3. An optical pulse generator for optical soliton communications comprising:

   a semiconductor laser (1) for continuously oscillating an output light at a single wavelength;
   a sinusoidal voltage generator (5) for generating a sinusoidal voltage;
   a first semiconductor electro-absorption type optical modulator (2) for modulating the intensity of the output light from said semiconductor laser by the sinusoidal voltage;
   a second semiconductor electro-absorption type optical modulator (8) for modulating the intensity of the output light from said first semiconductor electro-absorption type optical modulator by the sinusoidal voltage to provide optical short pulses;
   a first DC voltage source (3) for applying a reverse DC voltage to said first semiconductor electro-absorption type optical modulator (2) so that the output light from said semiconductor laser is sufficiently extinguished;
   a second DC voltage source (13) for applying a reverse DC voltage to said second semiconductor electro-absorption type optical modulator (8) so that the output light from said first semiconductor electro-absorption type optical modulator is sufficiently extinguished, and
   a delay circuit (10) between said second semiconductor electro-absorption type optical modulator (8) and said sinusoidal voltage generator (5), for delaying the sinusoidal voltage for a predetermined period.

Fig. 1A

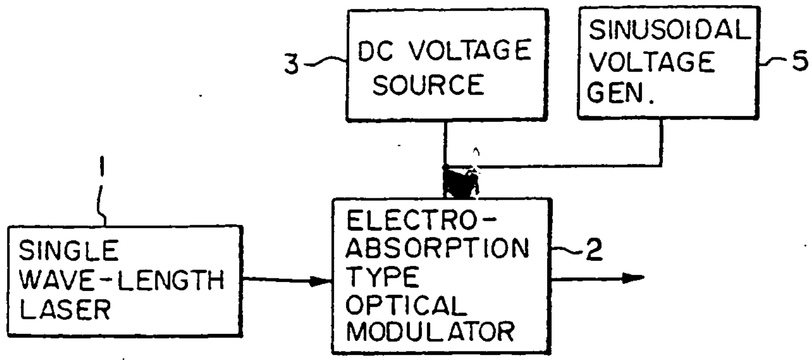

DC VOLTAGE SOURCE
3
SINUSOIDAL VOLTAGE GEN.
5
1
SINGLE WAVE-LENGTH LASER
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR
2

Fig. 1B

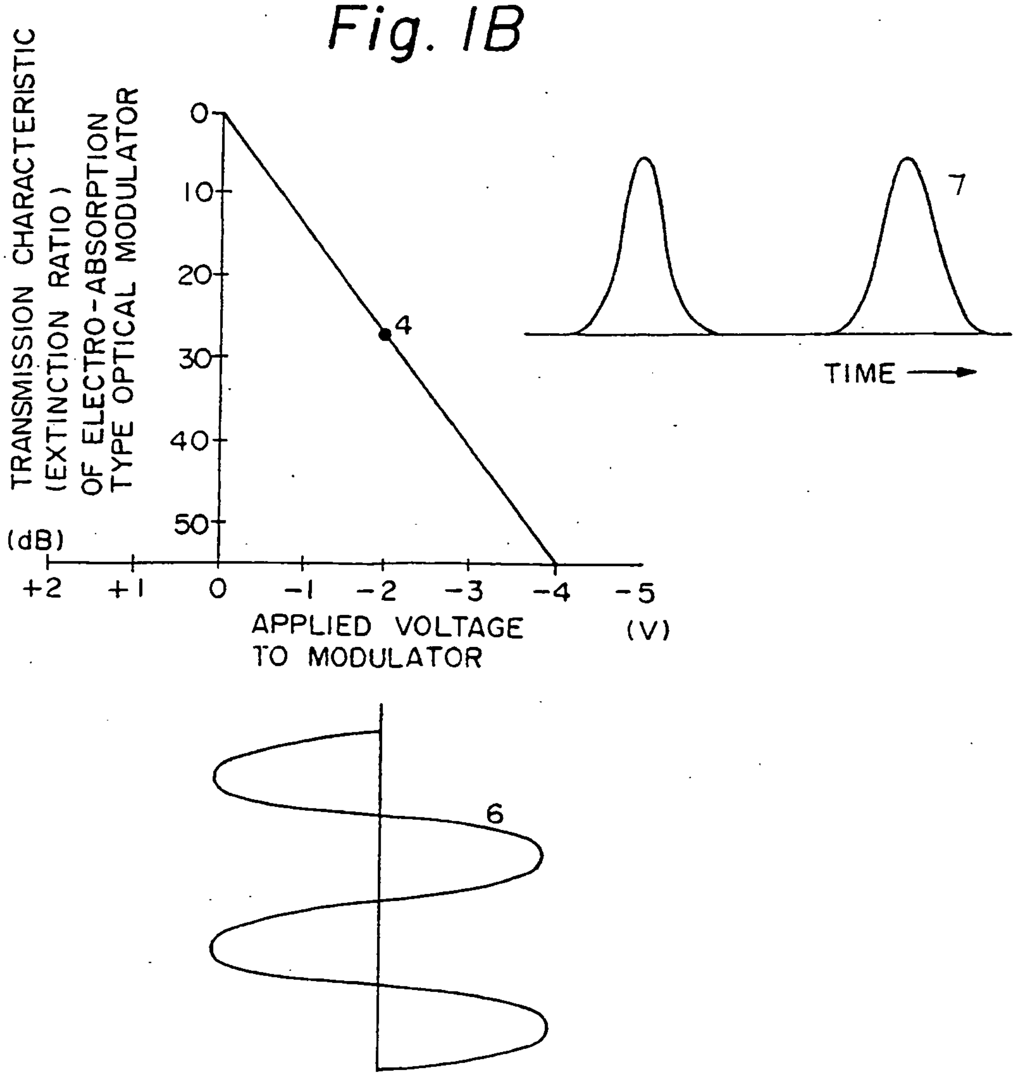

TRANSMISSION CHARACTERISTIC (EXTINCTION RATIO) OF ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR
(dB)
0
10
20
30
40
50
4
+2
+1
0
-1
-2
-3
-4
-5
APPLIED VOLTAGE TO MODULATOR
(V)
7
TIME
6

Fig. 3A

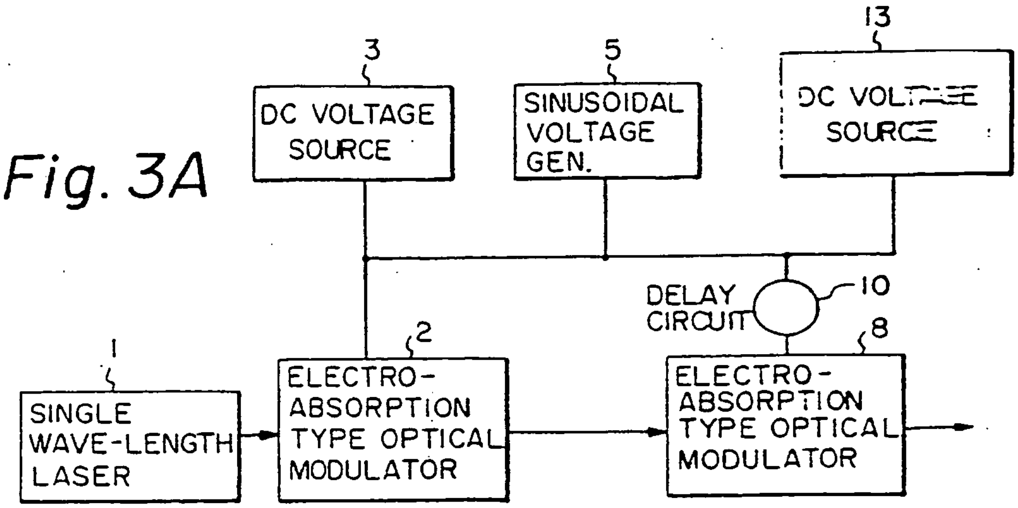

3
DC VOLTAGE SOURCE
5
SINUSOIDAL VOLTAGE GEN.
13
DC VOLTAGE SOURCE
DELAY CIRCUIT
10
1
SINGLE WAVE-LENGTH LASER
2
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR
8
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR

Fig.3B

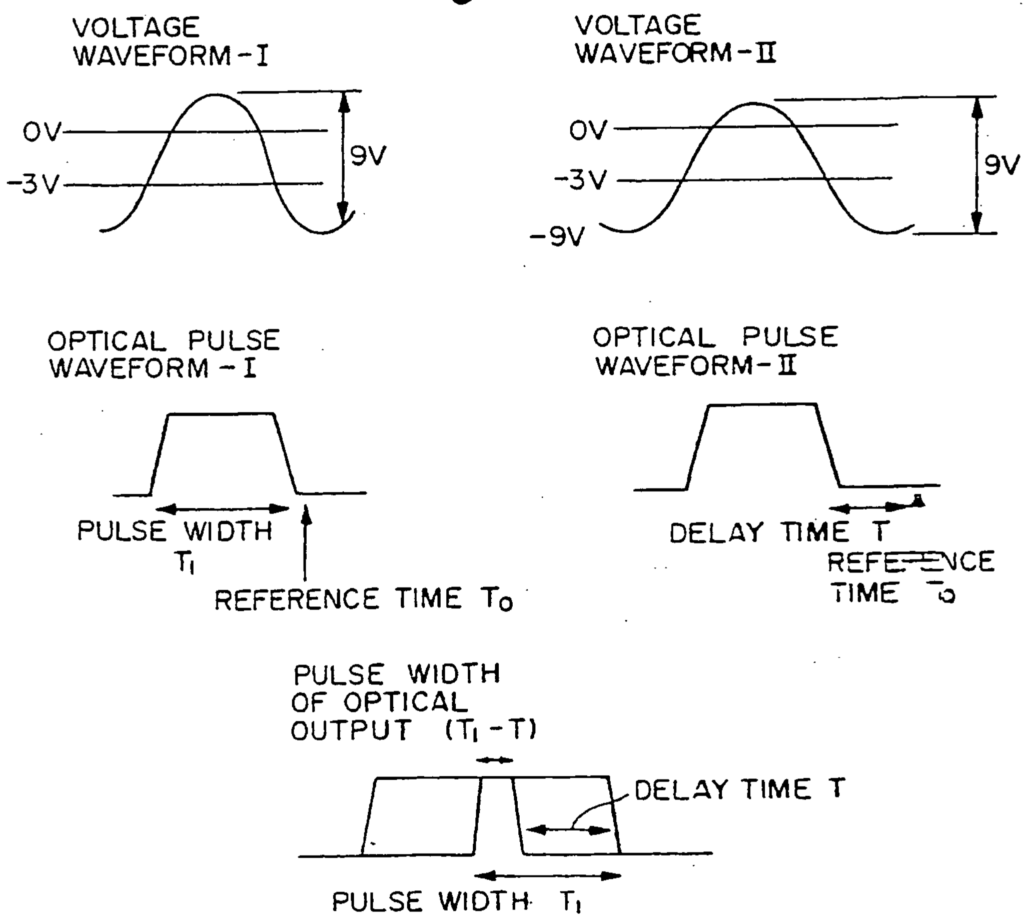

VOLTAGE WAVEFORM - I
0V
-3V
9V
VOLTAGE WAVEFORM - II
0V
-3V
-9V
9V
OPTICAL PULSE WAVEFORM - I
PULSE WIDTH T_1
REFERENCE TIME T_0
OPTICAL PULSE WAVEFORM - II
DELAY TIME T
REFERENCE TIME T_0
PULSE WIDTH OF OPTICAL OUTPUT $(T_1 - T)$
DELAY TIME T
PULSE WIDTH T_1

Fig. 5

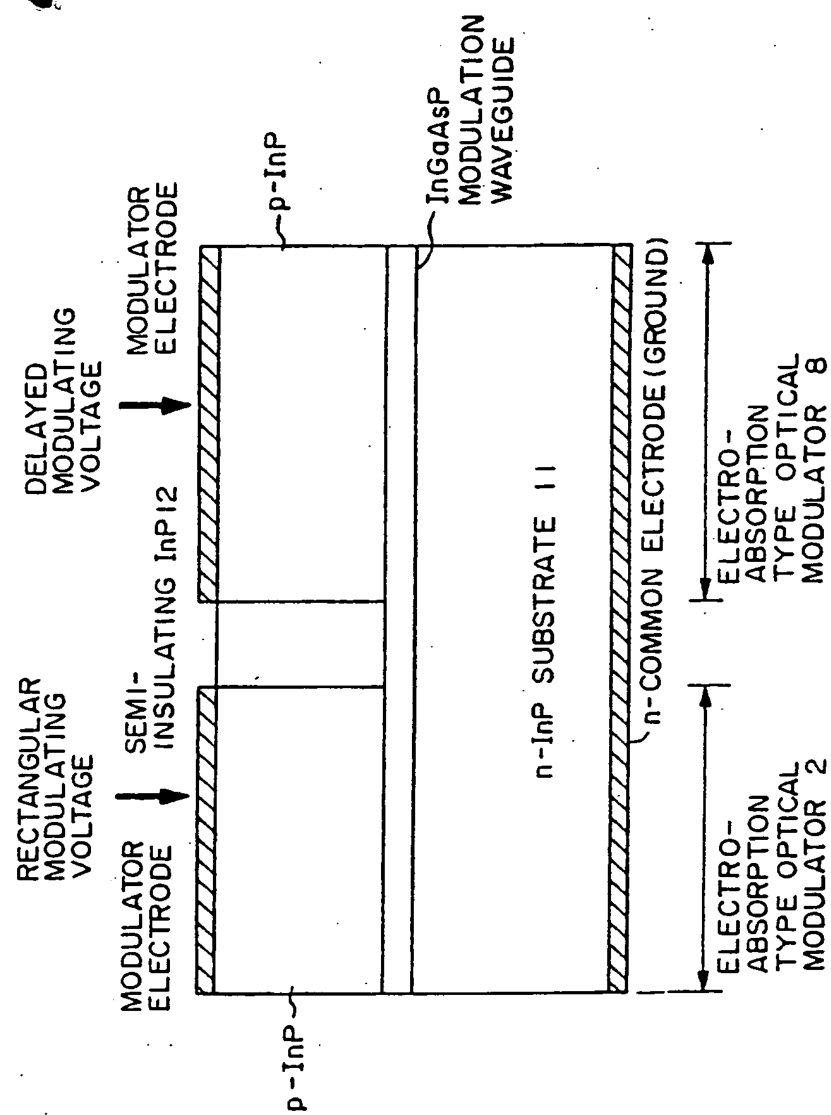

RECTANGULAR MODULATING VOLTAGE
MODULATOR ELECTRODE
SEMI-INSULATING InP 12
DELAYED MODULATING VOLTAGE
MODULATOR ELECTRODE
p-InP
InGaAsP MODULATION WAVEGUIDE
p-InP
n-InP SUBSTRATE 11
n-COMMON ELECTRODE (GROUND)
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR 2
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR 8

Fig. 7

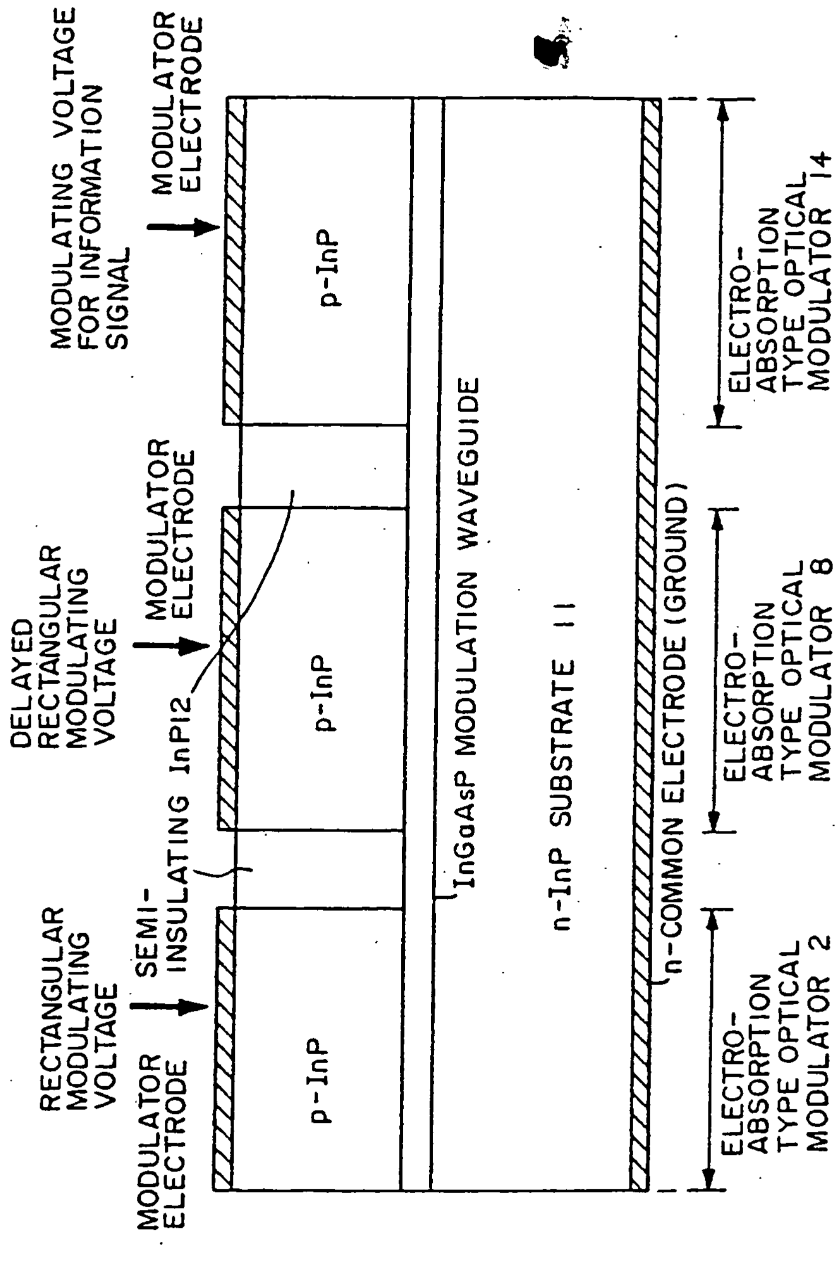

MODULATING VOLTAGE FOR INFORMATION SIGNAL
MODULATOR ELECTRODE
DELAYED RECTANGULAR MODULATING VOLTAGE
MODULATOR ELECTRODE
RECTANGULAR MODULATING VOLTAGE
SEMI-INSULATING InPI2
MODULATOR ELECTRODE
p-InP
p-InP
p-InP
InGaAsP MODULATION WAVEGUIDE
n-InP SUBSTRATE 11
n-COMMON ELECTRODE (GROUND)
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR 14
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR 8
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR 2

Fig. 9

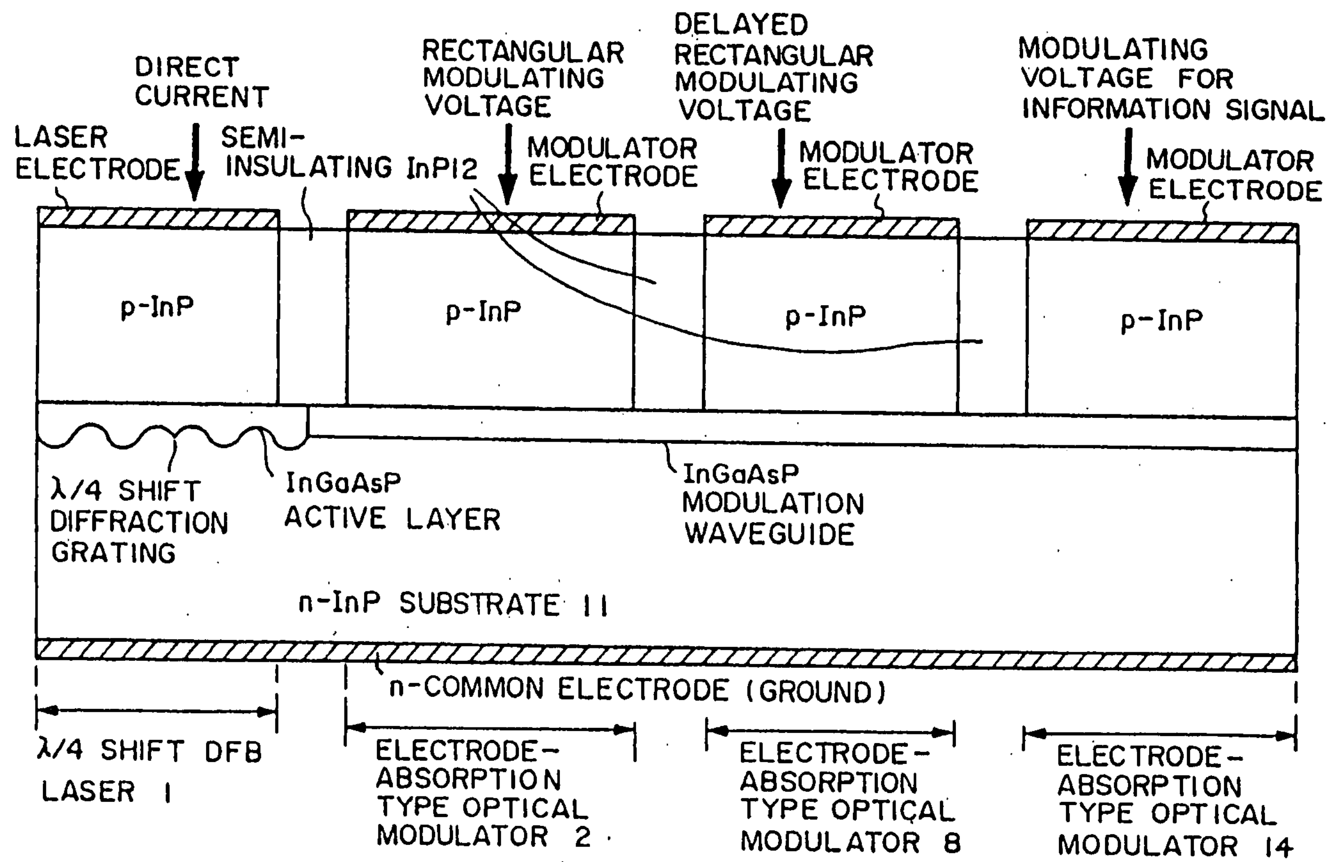
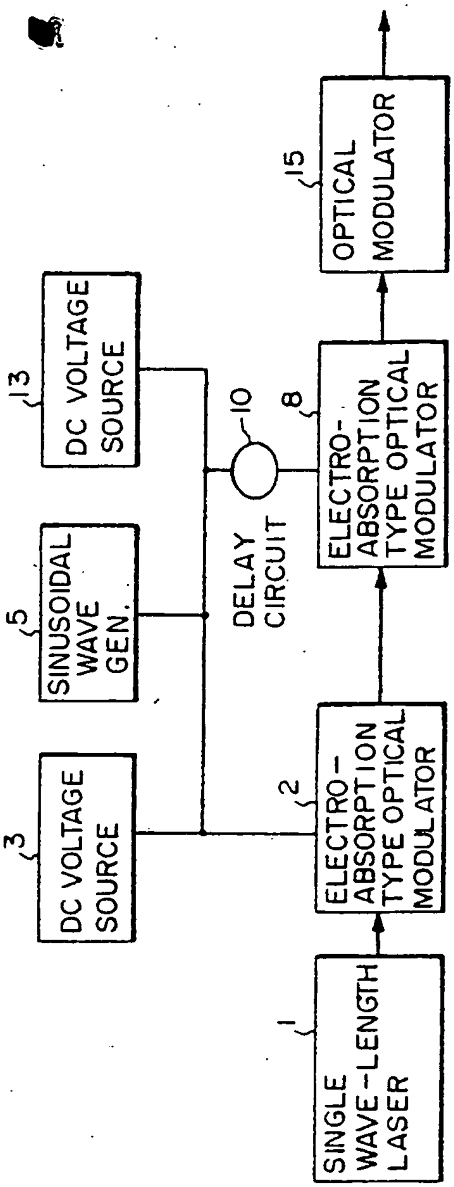

DIRECT CURRENT
LASER ELECTRODE
SEMI-INSULATING InP12
RECTANGULAR MODULATING VOLTAGE
MODULATOR ELECTRODE
DELAYED RECTANGULAR MODULATING VOLTAGE
MODULATOR ELECTRODE
MODULATING VOLTAGE FOR INFORMATION SIGNAL
MODULATOR ELECTRODE
p-InP
p-InP
p-InP
p-InP
λ/4 SHIFT DIFFRACTION GRATING
InGaAsP ACTIVE LAYER
InGaAsP MODULATION WAVEGUIDE
n-InP SUBSTRATE 11
n-COMMON ELECTRODE (GROUND)
λ/4 SHIFT DFB LASER 1
ELECTRODE-ABSORPTION TYPE OPTICAL MODULATOR 2
ELECTRODE-ABSORPTION TYPE OPTICAL MODULATOR 8
ELECTRODE-ABSORPTION TYPE OPTICAL MODULATOR 14

Fig. 12


3
DC VOLTAGE SOURCE
5
SINUSOIDAL WAVE GEN.
13
DC VOLTAGE SOURCE
10
DELAY CIRCUIT
1
SINGLE WAVE-LENGTH LASER
2
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR
8
ELECTRO-ABSORPTION TYPE OPTICAL MODULATOR
15
OPTICAL MODULATOR